Precision EW Measurements

Nov 10, 2016

Electroweak Lagrangian

- EW interactions governed by gauge group $SU(2)_L \times U(2)$
- Fermion Fields for i^{th} generation:
  - Left Handed Doublets:

$$\psi_{i\,L} = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}, \quad \begin{pmatrix} u_i \\ d_i^{'-} \end{pmatrix} \quad \text{where } d_i^{'-} = \sum_j V_{ij} d_j$$

  - Right Handed Singlets: $\psi_{i\,R}$
- Complete Lagrangian:

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4} f_{\mu\nu} f^{\mu\nu} \\
&+ \overline{R} i\gamma^\mu(\partial_\mu + i\frac{g'}{2} a_\mu Y)R + \\
&+ \overline{L} i\gamma^\mu(\partial_\mu + i\frac{g'}{2} a_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu)L \\
&+ \mathcal{D}^\mu\phi\mathcal{D}_\mu\phi - V(\phi^\dagger\phi) \\
&+ -\frac{g_f}{\sqrt{2}}\left(\overline{L}\phi R + \overline{R}\phi L\right)
\end{aligned}$$

Mass and Coupling Relationships (Lowest Order)

- With $\tan\theta = g'/g$ and defining v and λ as vev and quadratic term in $V(\phi^\dagger\phi)$:

$$\begin{aligned}
e &= g\sin\theta_W \\
\frac{G_F}{\sqrt{2}} &= \frac{1}{2}v^2 \to v = 246\ \mathrm{GeV} \\
M_H &= \sqrt{2\lambda}v \\
M_W &= \frac{1}{2}gv = \frac{ev}{2\sin\theta_W} \\
M_Z &= \frac{1}{2}\sqrt{g^2+g'^2} = \frac{ev}{2\sin\theta_W\cos\theta_W} = \frac{M_W}{\cos\theta_W} \\
M_\gamma &= 0
\end{aligned}$$

- Can choose 3 independent parameters and express everything else in terms of these 3

Program for Testing EW Theory

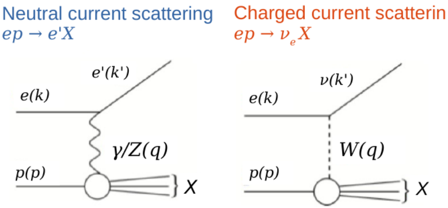
Three categories of test:

1. Studies of onshell W and Z properties
   - Discovery in 1983 (more next week)
   - High statistics Z studies in 1990's (LEP, SLC, Tevatron)
   - High statistics W studies in late 1990's, 2000's (LEP-II, Tevatron)
2. High statistics validation of "tree level" predictions
   - DIS results (HERA)
   - $e^+e^- \to W^+W^-$ (LEP-II)
   - Diboson production in pp collisions (LHC)
3. Tests that are sensitive to loop diagrams
   - Huge effort at LEP
   - Need quark masses as input (top mass from Tevatron)
   - Sensitive to Higgs mass

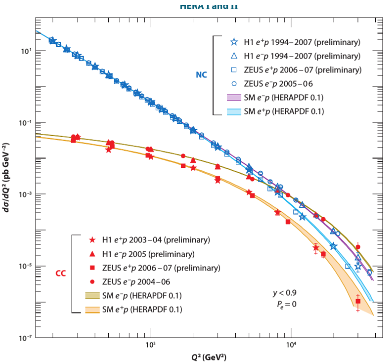
Note: Will review results in logical rather than chronological order

- Will defer details of hadron collider measurements until next week

Hera: DIS at large Q^2

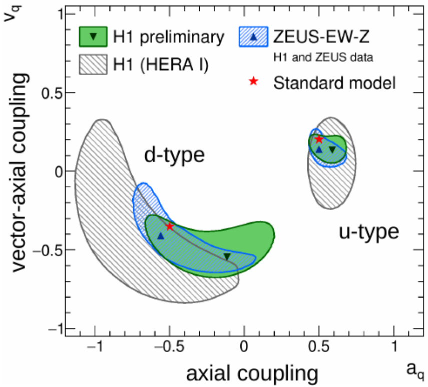


- Electron-proton collider
  - e^+ and e^-: $E_e = 27.6$ GeV
  - $E_p = 920$ GeV
  - Unpolarized running 1993-2000
  - Longitudinally polarized leptons
- Fits to high statistics data to determine EW parameters
- Leave vector and axial vector couplings of e, u-quarks and d-quarks free
- Constrain SM parameters
- Global PDF fits

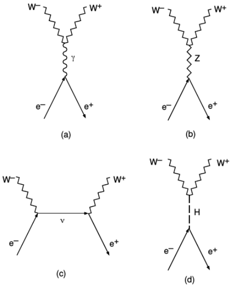


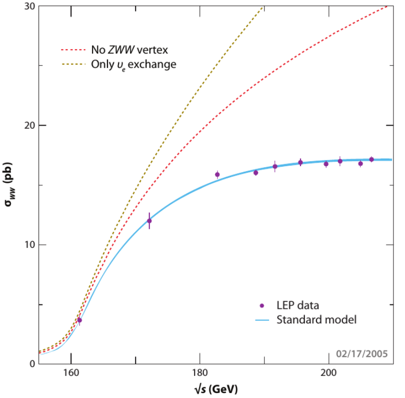
Measurements of NC couplings of quarks

- Axial and vector couplings determined by weak I_3 and Y
- Same equations as for leptons, but different numbers
- You will calculate these couplings on HW #9
- These couplings measured well at LEP, SLC
- HERA provides an alternative method



W Pair Production (LEP-II)

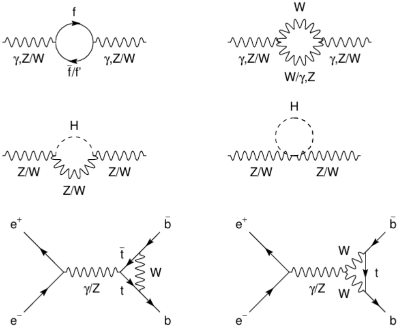




- Individual $J = 1$ partial-wave amplitudes for γ, Z and ν exchange rise $\propto s$
- Sum is well behaved
  - Result of gauge symmetry
- $J = 0$ amplitude for ν also diverges in absence of Higgs

Adding EW Radiative Corrections

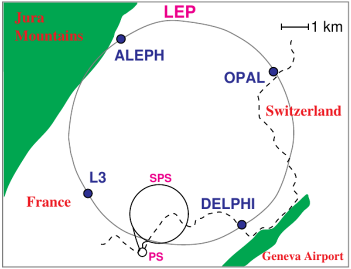
- Relationships among parameters defined on page 3 are modified by HO diagrams:

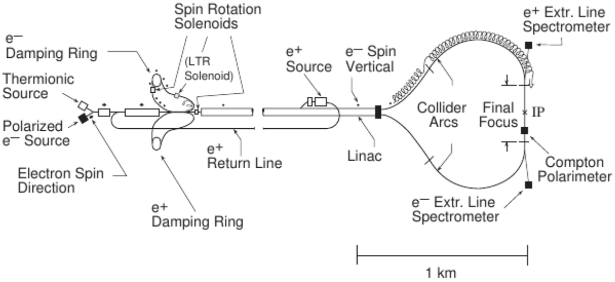


- But no new parameters (except quark and Higgs masses)
- In SM can still predict relationships between physical measurements, although formulae are more complicated
    - In BSM theories, new particles can propagate in these loops even if masses above E_{cm}
    - Discrepancies among measurements would indicate new physics

Testing the SM using $e^+e^- \to Z$

- LEP:
  - Four experiments
  - ~ 15.5 million $Z \to q\bar{q}$ and ~ 17.2 million $Z \to \ell^+\ell^-$ events analyzed
- SLC:
  - Much lower statistics than LEP
  - However e^- beam polarized

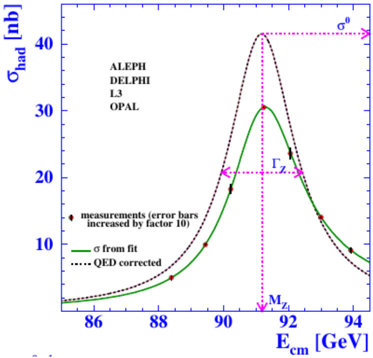


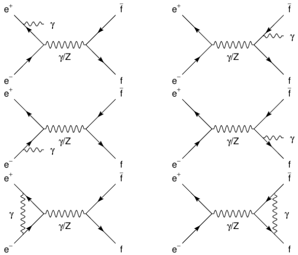


The Z Mass and Width

- LEP achieved 2 MeV precision on E_{cm}
- Scan over 7 energy points to measure resonance shape
- Correct for QED radiation to obtain M_Z and Γ_Z:

$$
\begin{aligned}
m_Z &= 91.1875 \pm 0.0021 \text{ GeV} \\
\Gamma_Z &= 2.49 \pm 0.0023 \text{ GeV}
\end{aligned}
$$





Measuring the number of light neutrinos

- Total decay width is sum over channels

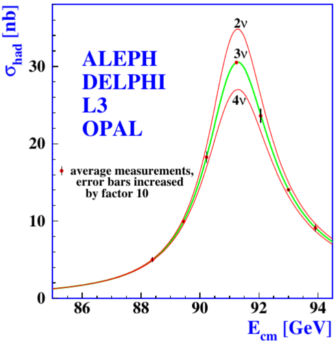
$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

- Cross sections (Breit-Wigner)

$$\begin{aligned} \sigma_{had} &= \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2} \\ \sigma_{\mu\mu} &= \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_Z^2} \end{aligned}$$

- Using lepton universality

$$\begin{aligned} \frac{\sigma_{had}}{\sigma_{\mu\mu}} &= \frac{\Gamma_{had}}{\Gamma_{\mu\mu}} \\ \Gamma_{inv} &= \Gamma_Z - 3\Gamma_{\mu\mu} - \Gamma had \\ \frac{\Gamma_{inv}}{\Gamma_Z} &= 1 - 3\frac{\Gamma_{\mu\mu}}{\Gamma_Z} - \frac{\Gamma_{had}}{\Gamma_Z} \end{aligned}$$



- If Γ_{inv} comes only from ν's

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\mu}\left(\frac{\Gamma_\mu}{\Gamma_\nu}\right)_{SM}$$

$$N_\nu = 2.984 \pm 0.008$$

Terminology: Effective Couplings

- Most radiative corrections can be absorbed into universal corrections to the Z propagator and $f\overline{f}$ vertex

  Some exceptions which we'll discuss later

- Define the following

$$\begin{aligned} \sin^2\theta^f_{eff} &= \kappa_f \sin^2\theta_W \\ g_{V_f} &= \sqrt{\rho_f}\left(T^f_3 - 2Q_f \sin^2\theta_{eff}\right) \\ g_{A_f} &= \sqrt{\rho_f} T^f_3 \end{aligned}$$

  where ρ_f and κ_f are calculable and universal

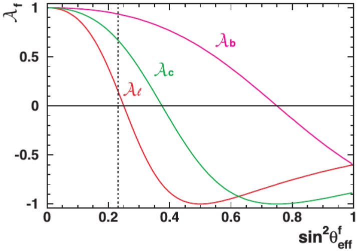
- Many LEP plots show dependence on $\sin^2\theta^f_{eff}$ instead of $\sin^2\theta_W$

Forward-Backward Asymmetry

- Angular distribution in QED: $1 + \cos^2\theta$
- Here θ is angle between ingoing e^- direction and outgoing fermion f direction
- Parity violating weak interactions add a $\cos\theta$ term
- Can see this effect either by measuring angular distribution or integrating over positive and negative $\cos\theta$

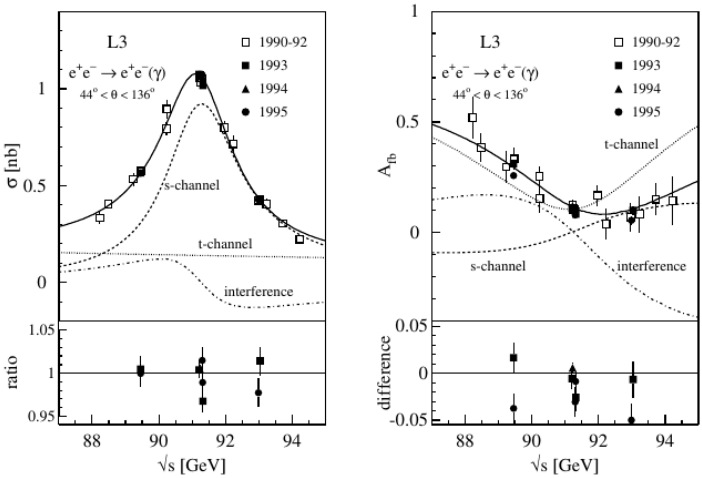
  Both have been done
- The integrated quantity

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



- Different asymmetries for leptons and for u-type and d-type quarks
- Note: e^+e^- channel has t-channel Feynman diagram

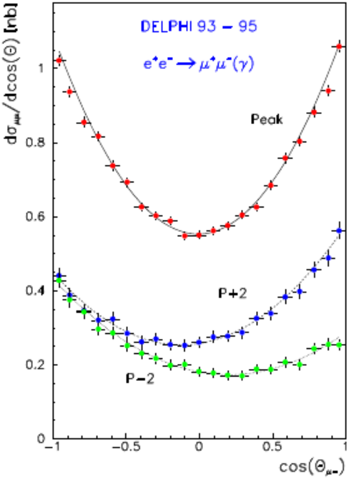
Cross section and A_{FB}^{ee} near the Z peak



Clear evidence for interference between t-channel and s-channel exchange

$A_{FB}^{\mu\mu}$

- Interference term between γ and Z
- Prediction depends strongly on E_{cm}
- Plot to right compares distribution for peak with that where $E_{cm} = E_Z \pm 2$ GeV

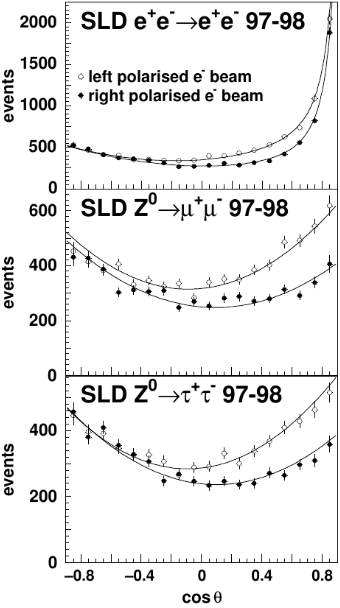


Polarized electron beam: A_{LR} from SLC/SLD

- Compare cross sections for e^-_L and e^-_R beams (unpolarized e^+)

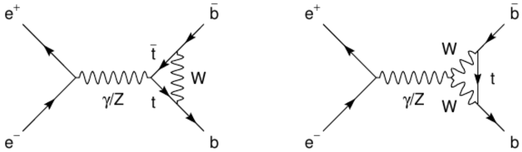
$$A_{LR} =\equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- Probes same couplings as A_{FB} but requires fewer events for same statistical precision on these couplings



How About the Quark Couplings?

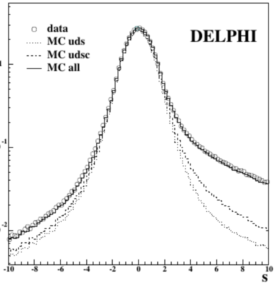
- Asymmetry measurements require distinguishing f and $\overline{f}$
- No clean way to do this for light quarks
  - Can try to measure jet charge, but large systematic uncertainties
  - We saw results from later HERA measurements on page 6
- Variety of techniques possible for "tagging" bottom and charm (HF)
  - Some distinguish q and $\overline{q}$ while others don't
- Want to determine
  - $A_{FB}^{b,c}$: Different τ_3 for b and c leads to different couplings
  - R_b and R_c: Sensitive to couplings but also in case of R_b to Zbb vertex

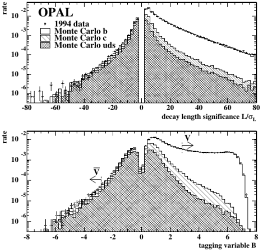


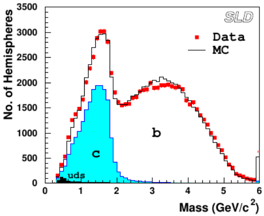
Flavor Tagging Methods

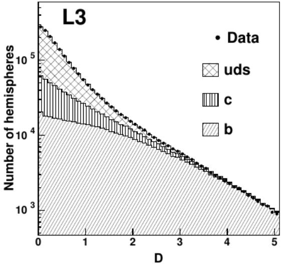
- b and c hadrons can be distiguished by
  - Long lifetime:
    $c\tau(B^+) \sim 491\ \mu$m
    $c\tau(B^0) \sim 455\ \mu$m
    $c\tau(B_s) \sim 453\ \mu$m
    $c\tau(D^+) \sim 311\ \mu$m
    $c\tau(D^0) \sim 123\ \mu$m
    $c\tau(D_s) \sim 150\ \mu$m
  - Semileptonic decays
    Distinguished q from $\overline{q}$
  - States with mass ~ 1.8 GeV for charm and ~ 5.2 GeV for bottom
- Many different techniques used
- Consistency of results helps validate the methods

Heavy Flavor Tagging Methods (I)

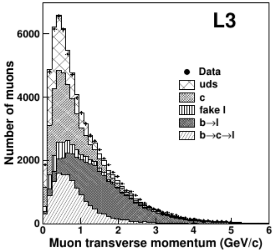


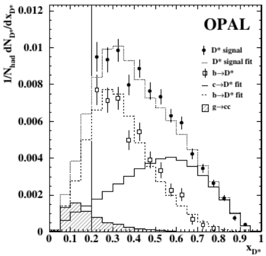


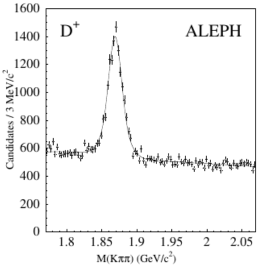




Heavy Flavor Tagging Methods (II)







R_b and R_c Measurements

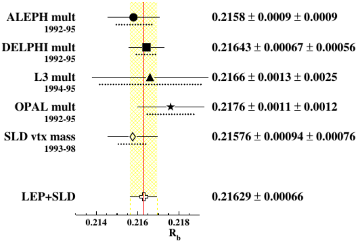
- Double Tag method (two hemispheres)

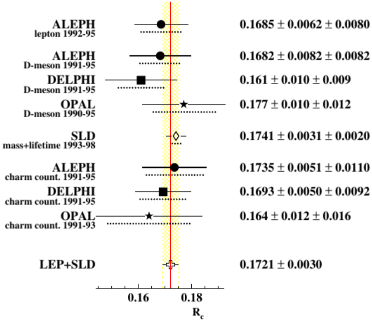
$$
\begin{aligned}
f_s &= \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c) \\
f_d &= \epsilon_b^{(d)} R_b + \epsilon_c^{(d)} R_c + \epsilon_{uds}^{(d)}(1 - R_b - R_c) \\
\epsilon_f^{(d)} &= (1 + C)\epsilon_f^2
\end{aligned}
$$

  where f_s and f_d are fraction of single and double tagged events and C is a small correction due to correlation between hemispheres

- Note: Requires simulation for the ϵ's and independent measurement of R_c
- Multitag method
  - Employ several tags and independent categories to refine the measurement

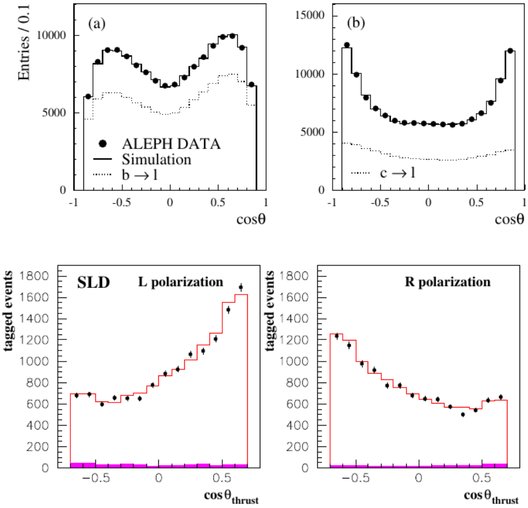
R_b and R_c Results



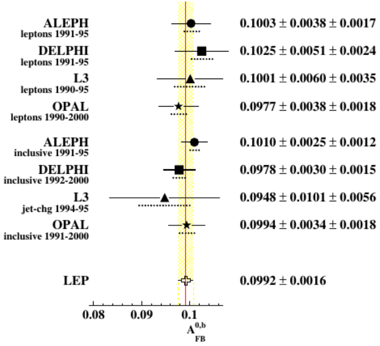


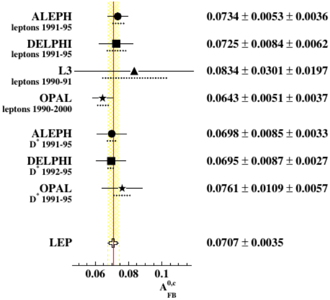
- Need to combine many methods to achieve necessary precision
- Important to understand correlations among systematic uncertainties
- EW group (with members from all LEP 4 experiments and SLD) worked for years to develop appropriate averages

A_{FB}^{b} and A_{FB}^{c} Distributions

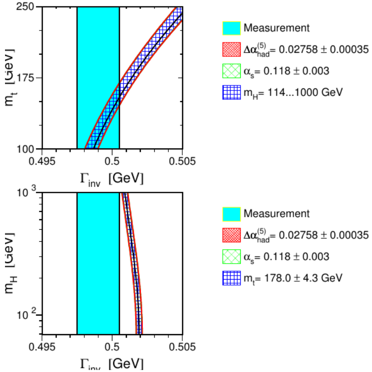


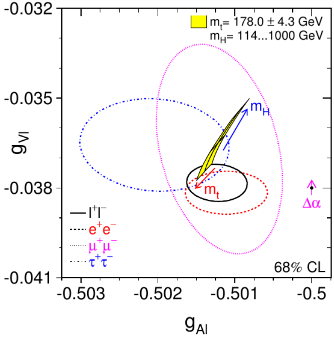
A_{FB}^b and A_{FB}^c Results





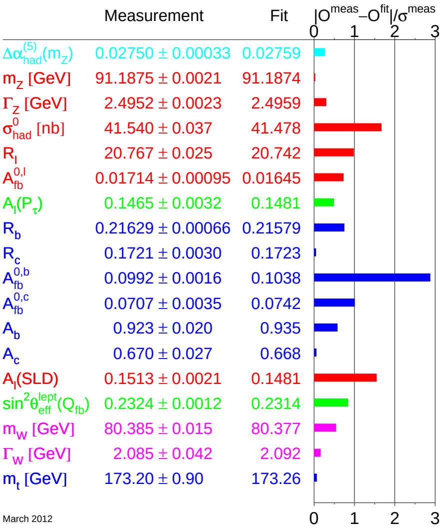
Comparing to the SM (I)

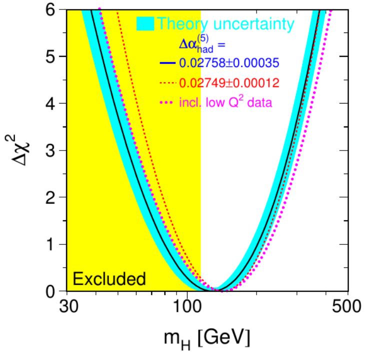




- Blue band is experimental measurement with uncertainty
- Lines show how predicted result depends on values of parameters (α, α_s, m_H, m_t, etc)

Comparing to the SM (II): Pre-LHC





- Global fit to many measurements that overconstrain parameters
- Status here was pre-LHC
- Included measurement of top mass from the Tevatron
- Fit for predicted Higgs mass